



Bioenergy and products from thermal pyrolysis of rice straw using plasma torch

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ABSTRACT

The aim of this work was to study the feasibility and operation performance of plasma torch pyrolysis of biomass wastes, taking rice straw as the target material. This novel method has several advantages including high heating rate, short heating time, no viscous tar and low residual char (7.45–13.78 wt.%) or lava. The productions of CO and H₂ are the major components (91.85–94.14 vol.%) in the gas products with relatively high reaction rates. The maximum concentrations of gaseous products occurring times are all below 1 min. Almost 90% of gaseous products were appeared in 4 min reaction time. The yield of H₂ increases with the increase of input power or temperature. With the increase of moisture (5–55 wt.%), the mass yields of H₂ and CO₂ also increase from the H₂O decomposition. However, due to the CO₂ production, the accumulated volume fraction of syngas decreases with the increase of moisture.

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1. Introduction

Biomass is a mixture of hemicellulose, cellulose, lignin and minor amounts of other organics. Rice straw is one of the favorable bioenergy sources because it is the residue from the end use of the rice. In Taiwan, the annual average of rice production was 1.6 million tonnes in 2001–2005 (Agriculture and Food Agency, COA, Executive Yuan, 2006). For every tonne of grain harvested, 1.35 tonnes of rice straw remain in the field (Kadam et al., 2000). Therefore, there is 2.2 million tonnes of rice straw generated every year. The rice straw is difficult for burning in most existing combustion systems. Its common treatment is on-site burning for producing manure. However, the open burning is harmful to the air quality and environment, including the CO₂ emission problem (Pütün et al., 2004).

Transform of the wastes into energy can be efficiently achieved applying thermochemical methods such as combustion, pyrolysis, partial oxidation and gasification (Shie et al., 2001, 2002, 2004a,b; Wu et al., 2003). Huang et al. (2008) employed the micro-wave-induced technology to pyrolyze the rice straw and yielded the H₂-rich fuel gas of nitrogen-free with H₂, CO₂, CO and CH₄ of 55, 17, 13 and 10 vol.%, respectively. The pyrolysis of biomass to produce syngas offers an alternative supply of energy other than fossil fuels. However, there are some problems occurred in conventional pyrolysis processes, such as low gas productivity and the generation of heavy tarry compounds, causing the corroding prob-

lem of the gas collection equipment and increasing the need for the further treatment of the gas produced (Bridgwater, 2003; Mérida et al., 2004; Yaman, 2004). These disadvantages and problems described above can be overcome via the use of thermal plasma pyrolysis which offers some unique advantages for biomass conversion, such as providing high temperature and heating rate, in comparison to conventional pyrolysis. Thermal plasma also offers the possibility of decomposition of biomass by pure pyrolysis in the absence of oxygen. The high energy-density and temperature associated with thermal plasmas and the corresponding fast reactions provide a potential solution for the problems occurred in conventional pyrolysis processes (Zhao et al., 2001; Shie et al., 2008; Tang and Huang, 2005).

In our previous study, a radio-frequency (RF) plasma thermolysis reactor was used for pyrolyzing the biomass waste of rice straw. The experiments were performed at various plateau temperatures of 740, 813, 843 and 880 K with corresponding loading powers of 357, 482, 574 and 664 W, respectively. The corresponding yields of gas products (excluding nitrogen) from rice straw are 30.7, 56.6, 62.5 and 66.5 wt.% with respect to the original dried sample and the corresponding specific heating values gained from gas products are about 4548, 4284, 4469 and 4438 kcal kg⁻¹, respectively, for the said cases. The corresponding combustible portions remained in the solid residues are about 64.7, 35, 28.2 and 23.5 wt.% with specific heating values of 4106, 4438, 4328 and 4251 kcal kg⁻¹ with respect to solid residues, while that in the original dried sample is 87.2 wt.% with specific heating value of 4042 kcal kg⁻¹. The best curve fittings render the frequency factor of 5759.5 s⁻¹, activation energy of 74.29 kJ mol⁻¹ and reaction

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order of 0.5 (Tu et al., 2008, 2009). In this study, the treatment of rice straw using thermal plasma torch as the heat source was further presented. Pyrolysis experiments were performed using carrier gas of N_2 injected at temperature ranges from 800 to 1000 K (2980–5160 W). Thus, the main objective of the present article is to assess the plasma torch pyrolysis of waste biomass of rice straw with different water contents and to examine the effects of operation parameters. It is the aim of present work to deal with the pyrolysis of rice straw with the viewpoint of providing products distribution at different water contents. The pyrolysis was performed using a pilot-scale plasma torch system in nitrogen atmosphere with 10 kW power capacities. The residual materials and non-condensable gases were collected and analyzed employing elemental analyzer, gas analytical instruments, and gas chromatography analyzers with thermal conductivity detector (GC-TCD).

2. Methodology

2.1. Materials

The biomass used in this study was rice straw. The rice straw sample was exposed under the sunlight for 10 days in order to get rid of the surface water. Then, the sample was broken by spiral breaker and sieved into 30–40 mesh (0.6–0.425 mm) and dried in a recycle ventilation drier for 24 h at 378 K before use. For comparison the effect of water content, the samples were adjusted by wet impregnated method to 5, 15, 35 and 55 wt.% water contents. The results of proximate analysis are 85.78, 9.67 and 4.55 wt.% of combustible value, ash and moisture, respectively. The heating value and elemental analyses of dry rice straw are reported in previous study (Tu et al., 2008). The combustible value of rice straw is 85.78 wt.% and the heating value is 4042 kcal kg⁻¹, supporting the use of rice straw as an energy source. The contents of C, H, N and S of rice straw are 41.41, 5.19, 0.95 and 0.2 wt.%, respectively (Table 1). The major mineral matter contents are Si, Al, Na, and Mg, and their values are 54803, 1113, 1030, and 990 ppmw, respectively. The total mineral matter is about 59619.6 ppmw. The total value of oxide compounds of mineral matter is about 12.5 wt.% (125074.8 ppmw) and is near with that of ash (11.7 wt.%) (Tu et al., 2008).

2.2. Plasma torch operational procedure

The pilot-scale apparatus used and the experimental procedures for the plasma torch pyrolysis of rice straw are shown in Fig. 1. A 10 kW plasma torch was used for the pyrolysis purpose.

For batch feeding, a sample of known pelletized mass (10 g) was placed on the sample input apparatus for feeding the sample material. The flow rate of carrier gas of N_2 (99.99%) (Q_N) was adjusted to the desired value, say 5 L min⁻¹ at 101.3 kPa (1 atm) and 293 K, and was controlled by a rotameter. For the power supply, the power supply control unit (chopper) (Taiwan Plasma Corp.) of plasma torch reactor was set at specific power (P_L) in the range of 2–6 kW for the temperatures (T) from 700 to 1000 K, respectively. P_L for the plasma torch used has a maximum power output of 10 kW. After the ignition by trigger, T can also be adjusted via Q_N or current from chopper (I_C). The primary sample feeding system consists of a closed cylinder hopper with upper and lower covers. The hopper has a maximum size of 45 mm diameter and 55 mm length. The dried sample was placed in the hopper that can be enclosed by upper and lower covers. The covers were alternatively opened for feeding. For an accurate comparison of the effects from temperatures, the feeding type used in this study was batch feeding with a 10 g sample for one run at a set temperature or supply power. For the easy delivering and feeding, the rice straw was pelletized to a cylinder with the pellet size of 10 mm diameter and 20 mm length. The plasma torch converts electrical to thermal energy. The applied high voltage on the electrodes results in electric discharges, which in turn generate the current flowing from the anode (+) to the cathode (–) through the gas passing by. The ignition gas such as N_2 is initially introduced and ignited as the voltage is high enough, forming plasma torch. After the ignition of plasma torch, the carrier gas such as N_2 is then introduced. A certain percentage of its molecules are partially or totally ionized, using the dissipation of resistive energy which also makes the gas sufficiently hot. The ionized gas is thus in plasma state. The reactor is comprised of a crucible, with approximate 1 L in capacity. Two shells were used for refractory insulation in the reactor with outer and inner layers of 4 and 8 cm thickness which can tolerate the temperatures as high as 1673 and 2073 K, respectively. The plasma was ejected from the torch into the reactor. A thermocouple was inserted into the reactor for measuring the surrounding temperature of plasma gas. The power supply was controlled via the feedback information from temperature readings. The system was operated under atmospheric pressure. The effluent gas surrounded by cooling water flowed through a rotameter and into a water-cooling bath, and then vented to a quench system. Because the synthesis gas may contain acid gases (such as HCl or SO_2), the water-cooling bath can remove water-soluble components of the off-gas including hydrochloric acid, most

Table 1
Elemental analysis of rice straw and solid residues at various temperatures and moistures.

Element	Target temperature ± 20 (K) Moisture	773 K 5 wt.%		873 K 5 wt.%		873 K 15 wt.%		873 K 35 wt.%		873 K 55 wt.%		973 K 5 wt.%	
		b		b		b		b		b		b	
		c	c	c	c	c	c	c	c	c	c	c	c
C	41.41 (0.11) ^d	21.42 (3.56)	2.95	33.45 (4.17)	4.38	22.38 (7.07)	2.34	13.8 (6.63)	1.39	18.49 (8.88)	1.38	0.46 (0.08)	0.05
H	5.19 (0.06)	1.64 (0.22)	0.23	1.59 (0.17)	0.21	1.14 (0.25)	0.12	0.61 (0.16)	0.06	0.82 (0.32)	0.06	0.31 (0.03)	0.03
N	0.95 (0.03)	0.4 (0.02)	0.06	0.71 (0.05)	0.09	0.76 (0.25)	0.08	0.35 (0.09)	0.04	0.66 (0.23)	0.05	0.22 (0.01)	0.02
S	0.2 (0.05)	0.07 (0.09)	0.01	0.28 (0.24)	0.04	0.32 (0.28)	0.03	0.18 (0.16)	0.02	0.2 (0.13)	0.01	0.22 (0.04)	0.02
C/H ratio (wt./wt.)	7.98	13.06		21.04		19.63		22.62		22.55		1.48	
			13.78 ^e		13.09 ^e		10.45 ^e		10.08 ^e		7.45 ^e		10.28 ^e

^a Dry basis of rice straw = 9.5 g and 10 g totally.

^b Based on mass of residue.

^c Based on original mass of raw rice straw.

^d Numbers in parentheses are standard deviations (σ_{n-1}).

^e Mass ratio of residue to raw rice straw.

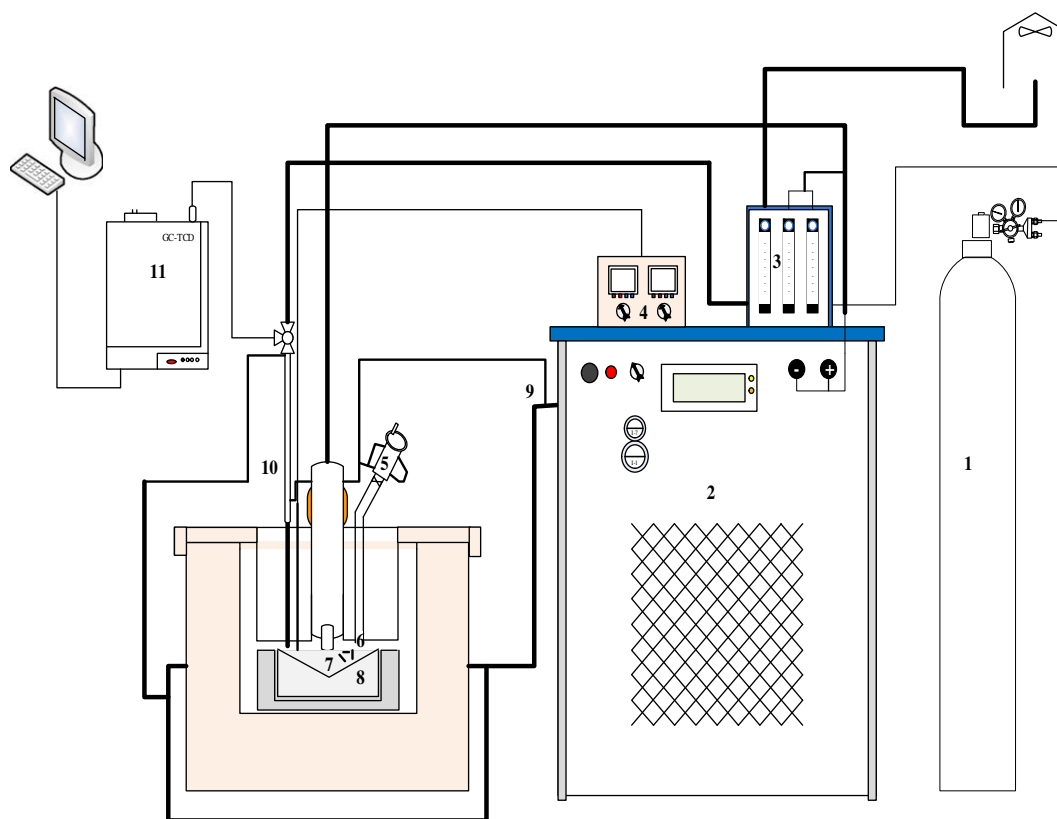


Fig. 1. Schematic diagram of apparatus for the 10 kW plasma torch. (1) Nitrogen cylinder, (2) power supply chopper and cooling system, (3) gas flow rate controller, (4) thermo detector, (5) sample input apparatus, (6) sample, (7) plasma torch and reactor, (8) crucible, (9) circulating water pipe, (10) outlet line, (11) gas detectors and analytical instruments.

oxides of sulfur and suspended particles, prior to discharge to the quench system. In order to measure the gas products, a gas chromatography was used for the analysis. For the analysis of gas products, a Thermo Scientific FOCUS GC Gas Chromatograph GC-TCD with a Supelco packing column (60/80 carbonxen-1000, 15 ft long, 2.1 mm i.d.) was used. The operation conditions were set as follows: injector temperature 453 K, detector temperature 513 K, column temperature (following the sampling injection) being held at 513 K for 10 min, helium carrier gas flow rate 30 mL min⁻¹ for A and B columns, and sample volume 2 mL. Several duplicate experimental runs were performed in order to get the correct values.

2.3. Elemental analyses

The elemental analyses for the residues from the plasma pyrolysis of rice straw were made on a Perkin–Elmer, Norwalk, CT2400 elemental analyzer with 0.3 wt.% accuracy. The elements of C, H and N were analyzed via Heraeus CHN-O-RAPID, and S analyzed via Tacussel Coulomax 78 automatic coulometric titrator.

2.4. Chemicals

The gas standards used for analyses were 99.9999% N₂, and 99.9% CO₂, CO, H₂, HCl and SO₂. Quantitative analysis of gaseous products was based on the calculation using the linear calibration response equations of standards. The equation was generated for each of gas standards using a minimum of five different concentrations with three replicates at each concentration. All correlation coefficients (r^2) of linear calibration response curves were great than 0.996.

3. Results and discussion

3.1. Characteristics of residues of rice straw for the plasma torch pyrolysis

The elemental analysis of rice straw and its residues at different temperatures and moistures for plasma torch pyrolysis are presented in Table 1. It indicates that carbon (C) and hydrogen (H) are the major elements in solid residues (excluding oxygen). It is obvious that the sulfur and nitrogen are rare and can be neglected. The C/H ratio in solid residues increase from raw material of 798–873 K with 35 wt.% moisture of 22.62. The escaped rate of H is larger than that of C in this range. At 873 K with 55 wt.% moisture, C/H ratio is almost equal to that of 873 K with 35 wt.% moisture, meaning that the increase water content did not change the C/H ratio after 35 wt.% moisture. It is also needed to note that the C/H ratio decreased drastically to 1.48 and almost all the elements are near zero (0.02–0.05 wt.%, relative to raw rice straw). Therefore, the residue in this high temperature or input power is almost lava. The weight percentages of residue are between 7.45 and 13.78 wt.% for the reaction temperature of 973 K with 5 wt.% moisture to 773 K with 5 wt.% moisture, respectively. From the lowest residue ratio at 873 K with 55 wt.% of 7.45, it implies that the high moisture can enhance the reaction completely. Most of the biomass has about the same properties and this is the main advantage of using biomass for energy and resources production from plasma pyrolysis.

3.2. Effects of temperature in the instantaneous gaseous products

3.2.1. Carbon monoxide and hydrogen (syngas)

The instantaneous concentrations of CO [CO] and H₂ [H₂] in gaseous products at various temperatures (T) and reaction times

(t_{rsf} = reaction time of solid sample in furnace after loading) are shown in Fig. 2a and b, respectively. From Fig. 2a, the maximum instantaneous concentrations and the corresponding t_{rsf} of CO occur at (1) 284,335 ppmv and 0.25 min for 773 K, (2) 382,226 ppmv and 0.25 min for 873 K and (3) 276,829 ppmv and 0.25 min for 973 K, respectively, with 0.5 min sampling interval. Fig. 2b shows that the maximum instantaneous $[\text{H}_2]$ occur at 0.25 min with $[\text{H}_2]$ of 164,893 ppmv for 773 K, 234,100 ppmv for 873 K and 197,817 ppmv for 973 K, respectively, with 0.5 min sampling interval. The productions of CO and H_2 are the major components in the gas products with the temperatures yielding the maximum concentrations at 873 K with relatively high reaction rates. The conversion of C to CO is more vigorous than the formation of H_2 as indicated in Fig. 2a and b with $[\text{CO}]$ higher than $[\text{H}_2]$. The times for the occurrence of maximum instantaneous concentrations of CO and H_2 are all at the same time, saying 0.25 min. Almost 90% of gaseous products were appeared in 3 min reaction time. Therefore, comparing with the conventional thermal pyrolysis, the reaction time of 3 min is considerable shorter. Thus, the elevated heating rate of plasma torch allows the reaction reaching the condition with maximum product concentration quickly. Therefore, the plasma torch can be characterized with its elevated energy-density that allows the treatment of solid waste such as rice straw faster than the conventional thermal methods. The product syngas contains substantial sensible heat, which is amenable for heat recovery to improve the efficiency of the electricity generation subsystem. Moreover, after purification, it becomes an important source of hydrogen which is anticipated to be used in the future transport means employing fuel cell technology (Tendler et al., 2005). A typical composition of syngas is depending mainly on the waste input composition. In fact, the purified synthesis gas can have multiple end uses in a large-scale plant, such as hydrocarbon production (petrol), hydrogen (fuel cells, gas engines), ammonia production (fertilizers), methanol manufacture (chemical indus-

try) and electricity (Moustakas et al., 2005). Just like petroleum products, syngas can be converted into useful chemicals and fuels via different synthetic routes including methanol synthesis, higher alcohol synthesis, Fischer–Tropsch synthesis (FTS), etc. Fortunately, these by-products share value as commercial chemicals, fuel additives, or potentially fuels in their own right (He and Zhang, 2008).

3.2.2. Methane and carbon dioxide

Fig. 2c shows that the maximum instantaneous concentrations of CH_4 occur at 16,416 ppmv for 773 K, 20,750 ppmv for 873 K and 7534 ppmv for 973 K, respectively, all at 0.25 min reaction time with 0.5 min sampling interval. It is obvious that the maximum concentration of CH_4 is occurring at 873 K. After the reaction time of 1.25 min, the concentration of CH_4 can be neglected. However, the maximum concentrations of CH_4 for these three temperatures are still far lower than those of the other gaseous products. From Fig. 2d, the maximum instantaneous concentrations of CO_2 appear at 36,181 ppmv for 773 K, 32,761 ppmv for 873 K and 23,397 ppmv for 973 K, respectively, all at 0.25 min reaction time with 0.5 min sampling interval. The concentrations of CO_2 decrease with the increase of reaction temperature. High temperature will inhibit the formation of CO_2 . Shie et al. (2008) pointed out that there are still some other pollutants appearing in the effluent gases, such as SO_2 , NO_x and HCl , and their maximum instantaneous concentrations are between 2.61 and 11.42 ppmv for plasma pyrolysis of sunflower-oil cake. Therefore, the analysis of these pollutants are neglected and no data shown detail in this study. From the points of view of suppression of pollutants emitted and of reduction of the power consumption; the reaction temperature may be controlled at certain temperature, such as below 973 K (Shie et al., 2008). Therefore, in the next section, we chose 873 K as the constant temperature for the testing the effects of water contents on the plasma pyrolysis of rice straw.

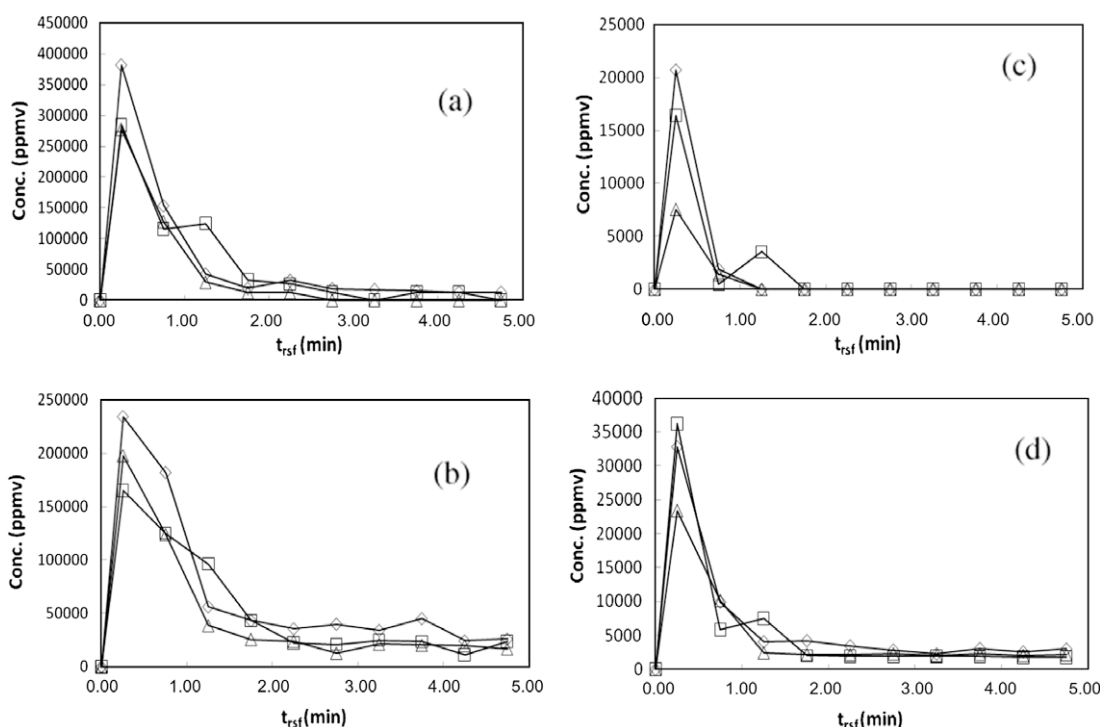


Fig. 2. Instantaneous concentrations in gaseous products from the pyrolysis of rice straw using plasma torch. $\square$, $\diamond$, $\triangle$: 773, 873, 973 K. t_{rsf} : reaction time of solid sample in furnace after loading. Moisture of rice straw = 5 wt.%. (a) CO, (b) H_2 , (c) CH_4 , (d) CO_2 .

3.3. Effects of moisture in the rice straw for the instantaneous gaseous products

3.3.1. Effects of moisture on Carbon monoxide and hydrogen (syngas)

Fig. 3a and b show the instantaneous concentrations of CO and H₂, respectively, in gaseous products from the pyrolysis of rice straw using plasma torch at different moistures. From Fig. 3a, the maximum instantaneous concentrations and the corresponding t_{rsf} of CO occur at (1) 307,450 ppmv and 0.75 min for 55 wt.%, (2) 236,067 ppmv and 0.25 min for 35 wt.% and (3) 247,502 ppmv and 0.25 min for 15 wt.%, respectively, with 0.5 min sampling interval. At 55 wt.% moisture, the occurring time of maximum concentration was delayed and the reason may be due to the longer time for energy transfer to decompose the water molecule. This was also proved by the case of 35 wt.% moisture for appearing two maximum concentration peak (0.25 and 0.75 time). Fig. 3b shows that the maximum instantaneous [H₂] occur with [H₂] of 234,722 ppmv at 0.75 min for 55 wt.%, 210,025 ppmv at 0.75 min for 35 wt.% and 162,029 ppmv at 0.75 min for 15 wt.%, respectively, with 0.5 min sampling interval. Relative to the case of 5 wt.% moisture, the occurring times of the maximum concentration of H₂ were all delayed and the energy transfer to decompose water for the production of H and O element was more clearly. Therefore, the production of H₂ was affected by the moistures obviously. The productions of CO and H₂ are the major components in the gas products with the temperature at 873 K and above 15 wt.% moistures. Almost 90% of gaseous products were appeared in 4 min reaction time. The energy intensity for the decomposition of H₂O is enough for the plasma pyrolysis of rice straw.

3.3.2. Methane and carbon dioxide

Fig. 3c shows that the maximum instantaneous concentrations of CH₄ for 873 K occur at 13,426 ppmv for 55 wt.% at 0.75 min, 14,119 ppmv for 35 wt.% at 0.25 min, 11,608 ppmv for 15 wt.% at 0.25 min, respectively, with 0.5 min sampling interval. It is obvious

that the maximum concentration of CH₄ is occurring at 5 wt.%. After the reaction time of 1.25 min, the concentration of CH₄ can be neglected. However, the maximum concentrations of CH₄ for these three moistures are still lower than that of 5 wt.% moisture, and far lower than those of the other gaseous products. From Fig. 3d, the maximum instantaneous concentrations of CO₂ appear at 46,374 ppmv for 55 wt.% at 0.75 min, 36,839 ppmv for 35 wt.% at 0.25 min, and 31,967 ppmv for 15 wt.% at 0.25 min, respectively, with 0.5 min sampling interval. The maximum concentration of CO₂ is occurring at 55 wt.%. It is obvious that moisture will increase the concentration of CO₂. Therefore, the torrefaction of rice straw for pretreatment in inhibiting of CO₂ production has its positive benefit.

3.4. Effects of temperature and moisture in the accumulated gaseous products

The accumulated masses of gaseous products from the pyrolysis of rice straw using plasma torch for three reaction temperatures and four moistures are shown in Table 2. The masses of all gas products increase with the temperature and moisture increase. At the same moisture (5 wt.%) of rice straw, the syngas ratio (=sum masses of syngas/dry basis of rice straw) increase from 20.03 wt.% at 773 K to 23.96 wt.% at 973 K, respectively. High temperature will enhance the production of gas products completely. For the syngas ratio of different moisture at 873 K, its value increases from 23.03 wt.% of 5 wt.% moisture to 46.73 wt.% of 55 wt.% moisture, respectively. Therefore, the optimum reaction condition should be controlled at 873 K and 55 wt.% moisture content. It is reasonable because the total mass of sample (mass of rice straw and water) increase with the increase of moisture content. It is also needed to note that the mass of H₂ increase from 5 to 55 wt.% moisture by 2.26 times at 873 K. Therefore, the addition of moisture enhances the production of H₂ obviously and this may be due to the decomposition of water to supply the hydrogen

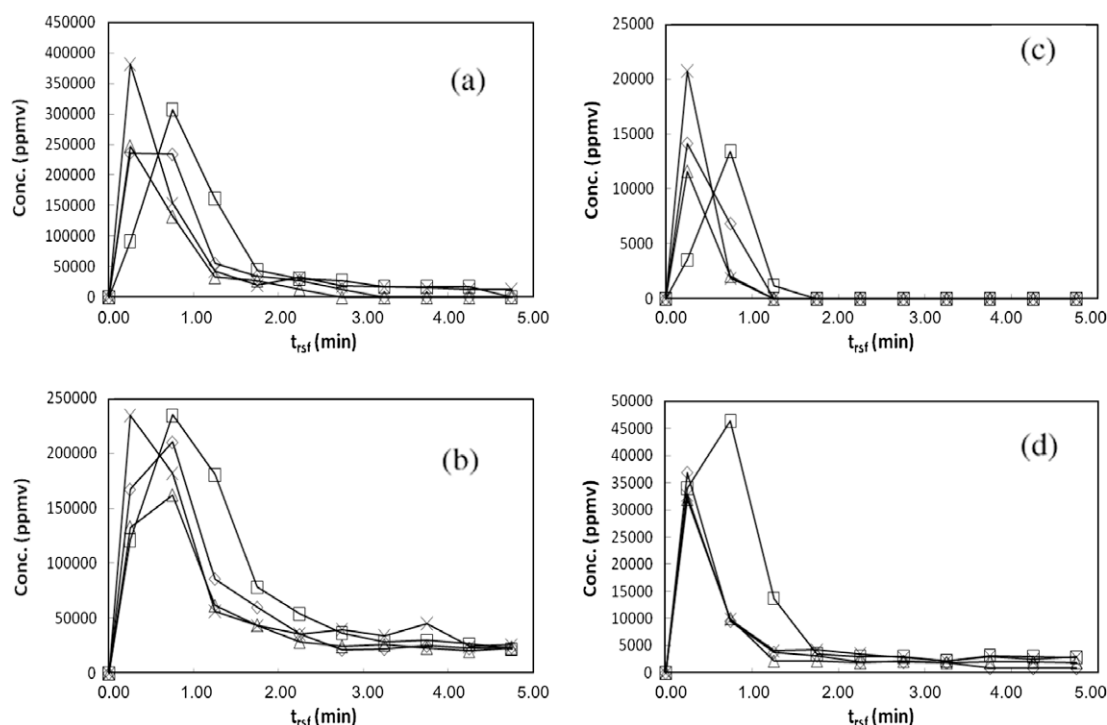


Fig. 3. Instantaneous concentrations in gaseous products from the pyrolysis of rice straw using plasma torch. x, $\diamond$, $\square$, $\triangle$: 5%, 15%, 35%, 55%. t_{rsf} : As specified in Fig. 2. Reaction temperature = 873 K. (a) CO, (b) H₂, (c) CH₄, (d) CO₂.

Table 2Accumulated masses of gaseous products and composition of effluent gases from the pyrolysis of rice straw using plasma torch (excluding of H₂O, NO_x, SO_x and N₂).

Target temperature ± 20 (K)	Moisture ^a (%)	CO			H ₂			CH ₄			CO ₂			Syngas yield ^b		Syngas ratio ^c	CO ₂ ratio ^d
Unit		mg	wt.%	vol.%	mg	wt.%	vol.%	mg	wt.%	vol.%	mg	wt.%	vol.%	wt.%	vol.%	wt.%	wt.%
773	5	1792.02 (391.66) ^e	80.54	50.15	111.17 (35.94)	4.95	42.98	33.18 (2.71)	1.53	1.69	282.1 (7.45)	12.98	5.18	85.49	93.13	20.03	2.97
873	5	2043.39 (560.73)	81.21	47.27	144.13 (35.1)	5.76	46.88	36.79 (4.1)	1.55	1.57	307.16 (197.43)	11.48	4.29	86.97	94.14	23.03	3.23
973	5	2115.63 (968.06)	78.89	45.4	160.23 (67.04)	6.03	48.59	23.2 (23)	0.75	0.76	368.72 (104.72)	14.33	5.25	84.92	93.99	23.96	3.88
873	15	2606.52 (621.87)	76.94	42.56	218.59 (6.62)	6.69	50.79	44.54 (31.3)	1.23	1.24	527.85 (237.35)	15.14	5.41	83.63	93.35	29.74	5.56
873	35	3454.56 (18.84)	79.62	44.84	269.77 (3.62)	6.22	49.03	68.11 (1.78)	1.57	1.55	558.44 (321.99)	12.59	4.58	85.84	93.87	39.2	5.88
873	55	4113.62 (491.67)	74.17	43.59	325.39 (36.12)	5.89	48.26	59.02 (18.76)	1.08	1.12	1036.51 (110.68)	18.86	7.03	80.06	91.85	46.73	10.91

^a Dry basis of rice straw = 9.5 g and 10 g totally.^b Syngas yield = syngas/sum of CO, H₂, CH₄ and CO₂.^c Syngas ratio = mass of syngas–gas/mass of dry basis of rice straw (9.5 g) × 100%.^d CO₂ ratio = mass of CO₂/mass of dry basis of rice straw (9.5 g) × 100%.^e Numbers in parentheses are standard deviations (σ_n).

source. The similar tendencies are also appeared in the accumulated masses of CH₄ and CO₂, especially for the CO₂ production. The mass of CO₂ increase from 5 to 55 wt.% moisture by 3.37 times at 873 K. The increase mass of CO₂ is due to the decomposition of water to supply the oxygen source. The moisture will enhance the pyrolysis reaction can also be proved from the residue ratio of rice straw (Table 1). The residue ratio of rice straw at 55 wt.% moisture after 873 K plasma pyrolysis is 7.45 wt.%, while the lowest value means the more complete reaction.

The accumulated mass and volume fractions (yields) of the effluent gaseous products relative to total mass and volume of gaseous products (CO, H₂, CH₄ and CO₂) (excluding carrier gas of N₂) in wt. and vol.% for three reaction temperatures and four moistures are shown in Table 2. It is noted that the rising rate of the accumulated mass fraction of 55 wt.% is the slowest comparing with the other moistures. This implies again that moisture will decrease the production rates of the gaseous products and delay the maximum concentration occurring time. From Table 2, the maximum accumulated mass fractions (or volume fractions) of syngas and the corresponding occurring moisture and temperature are 81.21 wt.% (47.27 vol.%) for CO at 5 wt.% moisture and 873 K, and 6.69 wt.% (50.79 vol.%) for H₂ at 15 wt.% moisture and 873 K, respectively. The maximum accumulated syngas yield and the corresponding occurring moisture and temperature is 86.97 wt.% at 5 wt.% and 873 K. The yield of H₂ increases with the increasing of temperature. Also from Table 2, the maximum accumulated CO₂ yield and the corresponding occurring moisture and temperature is 18.86 wt.% at 55 wt.% and 873 K. The addition of moisture increases the CO₂ yield obviously. The syngas in this study has more mass or volume yields at lower moisture and CO₂ yield has more mass or volume yields at higher moisture. The reason may be due to the contributions of the 5–55 wt.% moisture in the rice straw and the water content increases the yields of H₂ and CO₂ in pyrolysis via plasma technology. This implies again that the torrefaction process of the biomass can be controlled at elevated moisture for the different target compound product.

For the pyrolysis or gasification of rice straw, Worasuwannarak et al. (2007) applied the thermal gravimetry-mass spectrometry technique to study the pyrolysis behaviors of rice straw, yielding the pyrolysis products from rice straw at 873 K with compositions of char, H₂O, CO, CO₂, tar and sum of H₂ and CH₄ of 31, 25, 15, 15, 10 and 4 wt.%, respectively. Thus, other than H₂O, the CO and CO₂ are the dominant gas products, while H₂ and CH₄ are minor. Chen et al. (2003) employed the catalysts to pyrolyze the rice straw,

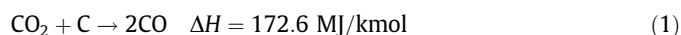
improving the gas yields at 1023 K with respect to the original un-dried sample containing about 10 wt.% H₂O from 36 wt.% without catalyst to 41, 42.2 and 46 wt.% with CaO, Na₂CO₃ and Cr₂O₃, respectively. However, even with the use of the catalyst of Cr₂O₃, the yield of tar is still as high as 10 wt.% at least.

Shie et al. (2008) used a 60 kW small pilot plasma torch to examine the pyrolysis of sunflower-oil cake. Depending on the operation temperatures, the main components of products were H₂ (47.35–56.13 vol.%), CO (39.82–51.17 vol.%), CO₂ (0.43–1.65 vol.%) and NO_x (1.67–6.65 vol.%). Hrabovsky et al. (2006) also used an experimental reactor equipped with the hybrid gas–water stabilized torch with arc power up to 160 kW to examine the gasification and pyrolysis of wood. Depending on the operation conditions, the main components of produced syngas were H₂ (28–46 vol.%), CO (44–68 vol.%), CO₂ (2–8 vol.%) and Ar (0.2–8 vol.%). The similar products from the treatment biomass using plasma technology are also appeared in other works (Zhao et al., 2001; Rutberg et al., 2004; Tang and Huang, 2005; Tendler et al., 2005; Van Oost, 2006; Tu et al., 2008, 2009). From these references, no complex hydrocarbons and tar were detected in plasma technologies.

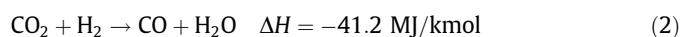
3.5. Reaction mechanism of the plasma torch pyrolysis of biomass

Demirbas (2002) proposed that there are four reactions about the plasma pyrolysis of biomass and these reactions are mentioned below.

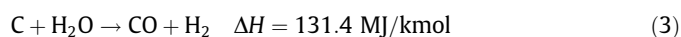
Boudouard reaction:



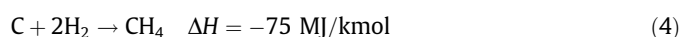
Water shift reaction:



Water–gas reaction



Methane production reaction



From the reactions listed above, water content will increase the production of H₂ and CO₂. Main reaction shows that heat is required during the reaction process. Plasma torch in one of the thermal plasma technology and worked in the atmosphere, and

it is very drastic due to the presence of highly reactive atomic and ionic species and the achievement of higher temperatures in comparison with other thermal methods. However, in fact, the extremely high temperatures (several thousand degrees in Celsius scale) occur only in the core of the plasma, while the temperature decreases substantially in the marginal zones (Moustakas et al., 2005). The electrical energy provides the energy need of the plasma torch which then transfers its energy to the substances to be treated, thereby triggering a dual simultaneous reaction processes in the plasma-chemical reactor. The organic compounds are thermally decomposed into simple compounds, such as syngas (CO and H₂) or their constituent elements. The inorganic materials are melted and converted into a dense, inert and non-leachable vitrified slag, that does not require controlled disposal. The electrical energy of plasma torch is transformed to plasma energy and then stored in the produced syngas. The main advantages are a better control of the composition of the produced gas, higher heat capacity of the gas, reduction of unwanted contaminants like tar and CO₂, and higher hydrocarbons (Van Oost et al., 2006).

Advantages of thermal plasma based technologies over conventional incineration include higher temperatures, independence of additional fuel and shorter residence times (Kezelis et al., 2004). A plasma based remediation system is one of the technologies that can prevent or reduce undesired pollutants in the by-products and end product (such as syngas or other gases). Tar content in the produced gas from the traditional pyrolysis or gasification of biomass always plays an important role because high tar content disables some potentialities of the further treatment of the gas produced. Plasma torch technologies for the pyrolysis or gasification of biomass not only yield high concentrations of syngas, but also result in low concentrations of tar in a gas phase, mostly below 10 mg Nm⁻³ (Hlina et al., 2006).

However, there is a vitally important concern of the use of electric energy, because it can substantially raise the operating cost of the use of plasma torch. In order to overcome parts of this problem, the need of electric energy for plasma torch may be supplied partly from the power generated via the use of product of syngas. For the energy consumption, Tendler et al. (2005) proposed that the energy productions of syngas for steam thermodynamic cycle (about 35% efficiency) and combined cycle (about 52% efficiency) were 5.35 and 7.96 MJ kg⁻¹ from wood, 5.06 and 7.52 MJ kg⁻¹ from RDF, and 10.37 and 15.27 MJ kg⁻¹ from car tyres, respectively. Comparison with the energy consumptions of processing the wood, RDF and car tyres for plasma torch gasification of 3.6, 3.82 and 6.66 MJ kg⁻¹, respectively, the energy stored in syngas are all higher than that energy consumption from the operation of plasma torch.

On the other hand, the investment costs of plants of plasma torch are typically 30–50% lower than those of incinerators of the same capacity (Ramachandran and Kikukawa, 2002). Another effect of the operation cost for plasma torch application is the cost of feedstock. Therefore, the best choice of feedstock is waste from biomass or waste organic materials. Consumption of agricultural residues for energy production would also reduce the environmental damage, for instance, CO₂ emission in treatment of agricultural residues. In generally, use of biomass substituting fossil fuels for electricity and heat production is less costly and more efficient for resource utilization than replacing gasoline or diesel for transportation.

4. Conclusion

In this study, a 10 kW torch plasma thermolysis reactor is used for pyrolyzing the biomass waste of rice straw. Almost 90% of gaseous products were appeared in 3 min reaction time. The inorganic

components were converted into non-leachable vitrified lava which is non-hazardous. The productions of CO and H₂ are the major components in the gas products with relatively high reaction rates. With the increase of moisture, the mass yields of H₂ and CO₂ also increase. The obtained data and information are useful for the rational operation and design of pyrolysis of rice straw via plasma torch.

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